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A Comparison of Center/TRACON Automation System and Airline Time of Arrival Predictions

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Abstract

Benefits from information sharing between an air traffic service provider and a major air carrier are evaluated. Aircraft arrival time schedules generated by the NASA/FAA Center/TRACON Automation System (CTAS) were provided to the American Airlines System Operations Control Center in Fort Worth, Texas, during a field trial of a specialized CTAS display. A statistical analysis indicates that the CTAS schedules, based on aircraft trajectories predicted from real-time radar and weather data, are substantially more accurate than the traditional airline arrival time estimates, constructed from flight plans and en route crew updates. The improvement offered by CTAS is especially advantageous during periods of heavy traffic and substantial terminal area delay, allowing the airline to avoid large predictive errors with serious impact on the efficiency and profitability of flight operations.

1. Introduction

Research to investigate the benefits of collaboration in arrival flow management between air traffic control service providers and major air carriers is ongoing at the NASA Ames Research Center, under the sponsorship of the Collaborative Arrival Planning (CAP) project. A discussion of the specialized hardware and software developed for service provider-carrier communication and preliminary results showing the benefits of data exchange have been reported by Zelenka et al. (ref. 1). This Technical Memorandum describes the portion of the CAP effort devoted to improving predicted time of arrival accuracy. Specifically, the report discusses the sharing of arrival time schedules generated by a set of NASA/FAA airspace management software tools known as the Center/TRACON Automation System (CTAS). In an exploratory project with American Airlines (AAL), arrival times predicted by CTAS, using aircraft trajectory modeling and dynamic airspace constraints, were provided to the airline as an alternative to its traditional forecasts based on flight plans and en route crew updates. It is shown that the CTAS predictions have greater accuracy and are potentially valuable for improving the efficiency of airline flight operations.

A need for closer collaboration between airlines and air traffic control facilities has arisen from several factors related to the increasing complexity of airline operations. These include: increased air traffic volume and aircraft delays, critical timing requirements in hub and spoke operations, and increased air carrier economic pressures. Domestic and world-wide air traffic is expected to grow to unprecedented levels over the coming two decades: revenue passenger miles worldwide of 1.7 trillion in 1996 are anticipated to reach 3 trillion in 2006, then 4.5 trillion in 2016 (ref. 2). Existing demands on the air traffic system routinely exceed the capacity of airports, leading to air traffic imposed ground and airborne delays of aircraft, estimated to cost domestic airlines as much as $3.5 billion per year (ref. 3). In the increasingly competitive airline industry, with its market-driven pricing and very thin profit margins, such economic operating penalties are magnified.

Of paramount importance in the efficient operation and profitability of an airline is adherence to its flight schedule. For large air carriers operating in “hub and spoke” networks, the maintenance of the carrier’s flight schedule at its hubs drives the business efficiency of the entire flight network, including outlying spokes. In a hub and spoke network, many aircraft arrive at a central hub airport in rapid succession and depart to other spoke cities with very little time at the airport gate. This allows an airline to offer service to more cities with fewer airplanes. The control of the hub arriving blocks or “banks” of aircraft, and their subsequent turn-around in departure banks of aircraft, is called “bank management.”

The American Airlines operational control center located in Ft. Worth, TX, called System Operations Control (SOC), manages over 650 jet aircraft through four major hubs, with over 2200 flight segments daily. Their largest hub, at Dallas Ft. Worth (DFW) airport, operates 58 gates and 9 major arrival/departure banks every day. The largest and most complex bank has over 60 aircraft arriving within 75 min, then 70 aircraft departing in the following 90 min. At maximum capacity during this bank, AAL connects over 6000 passengers, 9000 bags and 30 tons of cargo.

Reliable and efficient bank management is critical to the success of a hub and spoke airline. Closely-spaced arrivals and departures in hub and spoke networks are very sensitive to timing miscues, such as those caused by bad weather or airport congestion. Arrival timing miscues lead to missed passenger and crew connections, inefficient ground operations caused by incorrect gate assignments, and occasional aircraft diversions to alternate airports. These cause passenger inconvenience, flight delays and lost airline revenue.

The data generated and provided by the CTAS air traffic management tool are directly relevant to an air carrier's hub operations and associated bank management. The system's highly accurate time of arrival predictions, particularly during periods of airborne delay and holding, can assist an airline with several aspects of fleet operations. These include whether to hold spoke flights for a late incoming flight (the "hold-go" decision) and whether a flight should be diverted to an alternate airport or continue in airborne holding. Typically, departing spoke flights are held if an inbound feeder flight is expected to be no later than 15 min from its scheduled arrival time, but released if the feeder flight is over 15 min late. Such a holding threshold balances the need to maintain the fleet-wide scheduling against the desire to maintain individual spoke flights. The time separation between the last arrival in a bank and the first departure is critical to hub operations. Other factors that make specific aircraft arrival times critical include crew time limitations, gate availability, passenger connections and ground manpower. Late gate changes cause many problems due to special procedures, equipment needs and baggage processing demands. The efficiency of all such bank management issues is directly tied to the accuracy of aircraft time of arrival predictions.

Under the CAP project, real-time arrival scheduling and airspace management data supplied by CTAS software to en route controllers at the Ft. Worth Air Route Traffic Control Center (ARTCC) are being shared with airline operations personnel at the AAL SOC. The data exchange utilizes a specialized "CAP Display System" which captures the arrival schedule for AAL flights constructed by CTAS and used by the ARTCC controllers. Analysis (ref. 1) has shown that CTAS information sharing leads to improved predicted time of arrival accuracy, improved strategic fleet arrival planning and improved divert/no divert decisions when faced with uncertain airborne delays. No adverse impact on FAA air traffic control operations was found to have resulted from this experimental data interchange.

A brief technical background covering basic air traffic control concepts and the arrival time forecasting methods employed by AAL and CTAS is included as section 2 of this document. Sections 3 and 4 describe numerical and statistical methods for assessing arrival time accuracy and inferences from a comparison of CTAS and airline arrival time predictions. Some concluding remarks appear in section 5.

2. Background

2.1 Air Traffic Control Concepts

United States airspace is divided into contiguous regions known as "Air Route Traffic Control Centers" (ARTCCs). These regions, popularly called "Centers," provide air traffic control services to flights which are en route to, but still outside of, the immediate vicinity of a major airport. In figure 1, the darkly-shaded area shown on the U.S. map, and in enlargement, is the Ft. Worth ARTCC. This Center, with an east-west dimension of about 400 miles, is further divided into a number of subregions known as "sectors." One or more air traffic controllers directs flights traversing a sector to assure safe and efficient traffic flow.

The airspace within about 40 miles of a major airport is known as the "TRACON," an acronym for Terminal Radar Approach Control. The map in figure 1 shows the Dallas Ft. Worth (DFW) TRACON as a lightly-shaded region within the Ft. Worth ARTCC. TRACON air traffic controllers issue final instructions and clearances for arriving and departing aircraft. Air traffic entering the DFW TRACON from the Center is funneled through four reference points referred to as "cornerposts." A typical traffic pattern is illustrated in figure 2(a) by a set of aircraft "tracks" representing all AAL flights landing at DFW on April 22, 1998, between 4:30 PM and 6:30 PM CDT. These tracks are two-dimensional (X,Y) projections of three-dimen-

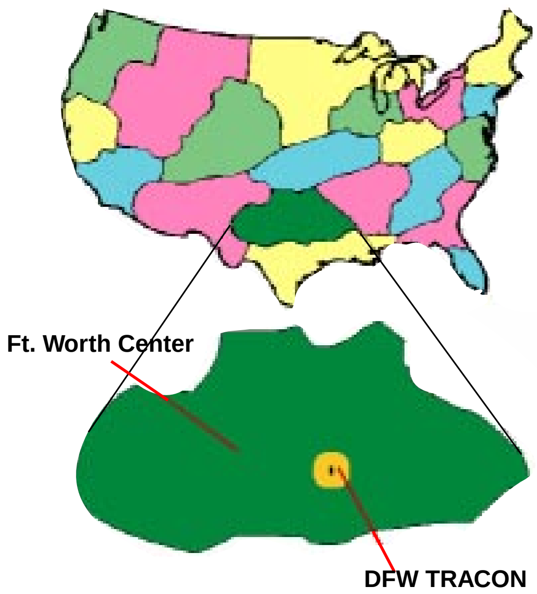

Figure 1. U.S. Air Route Traffic Control Centers.

sional aircraft trajectories constructed from radar position measurements. The tracks are seen to converge onto the cornerposts, marked as filled circles, and then to follow more restricted routes within the TRACON. Just distinguishable at the center of the diagram are the track-traced outlines of individual runways.

During periods of heavy traffic, known as rushes, the cornerposts serve as "metering fixes." Time-based metering is a procedure for constraining traffic entering the TRACON so that the rate of flow does not exceed the capacity or impact the safety of airport operations. To meet the constraints of metering, controllers may need to delay some aircraft. This may be done with speed reductions, temporary heading changes (vectoring) or holding patterns. Figure 2(b) illustrates aircraft tracks during a rush period with substantial controller-initiated delay. Many of these tracks show evidence of delay by vectoring, and a few also show indications of "fix balancing," a procedure whereby aircraft were reassigned from the overloaded top-left metering fix to the alternate fix at the bottom-left.

It is important to realize that the delay added during metering is not easily predicted by airlines that traditionally rely on arrival times estimated from flight plans and infrequent crew updates, and that the consequent uncertainty in arrival times may lead to disruption of the closely orchestrated pattern of hub and spoke operations.

2.2 Airline Time of Arrival Predictions

Major airlines estimate their flight arrival times by tracking time deviations from the nominal flight plans. The flight plan created for the flight crew by an airline's dispatcher includes estimated times for "out" of the airport terminal gate, take "off" from the ground, crossings of several navigational fixes en route, landing "on" the ground and parking "in" the destination airport terminal gate. The OUT/OFF/ON/IN times, commonly referred to as "OOOI" times, are critical to airline operations, as they determine whether an airline is running on or off schedule, and if off-schedule, to what degree. An airline too far off schedule begins to misconnect flights and suffer operational and economic losses.

The flight plan, once updated to reflect the actual takeoff time, is generally a good approximation of the en route or cruise portion of a flight. However, any unexpected re-routing or delays can significantly alter the flight's estimated landing or "ON" time. American Airlines' flight procedures call for the flight crew to update its time of arrival at "changeover," defined as nominally 20 to 30 min from landing. A typical sequence of OFF, changeover and ON times is illustrated by the schematic in figure 3. Although variable, flight crews typically provide an arrival time update once they receive the destination airport's Automated Terminal Information Service (ATIS). As ATIS is provided through a line-of-sight transmitter, such updating varies with the geography of the destination airport. At DFW, such changeover estimates are provided approximately 30-35 min from landing. These updated estimated ON times, called E/ON times, thus reflect any en route delays the flight has encountered. At AAL, the updated E/ON is broadcast back to the SOC through the Aircraft Addressing and Reporting System (ACARS).

Even if no en route deviations occur to alter the nominal flight plan navigational fix times, a flight is typically subject to terminal area flight plan deviations (e.g., speed decreases, vectoring) that significantly alter its ON time. Note that terminal area delays begin well outside the TRACON, typically starting approximately 30 min from landing at DFW. Such ATC ter-

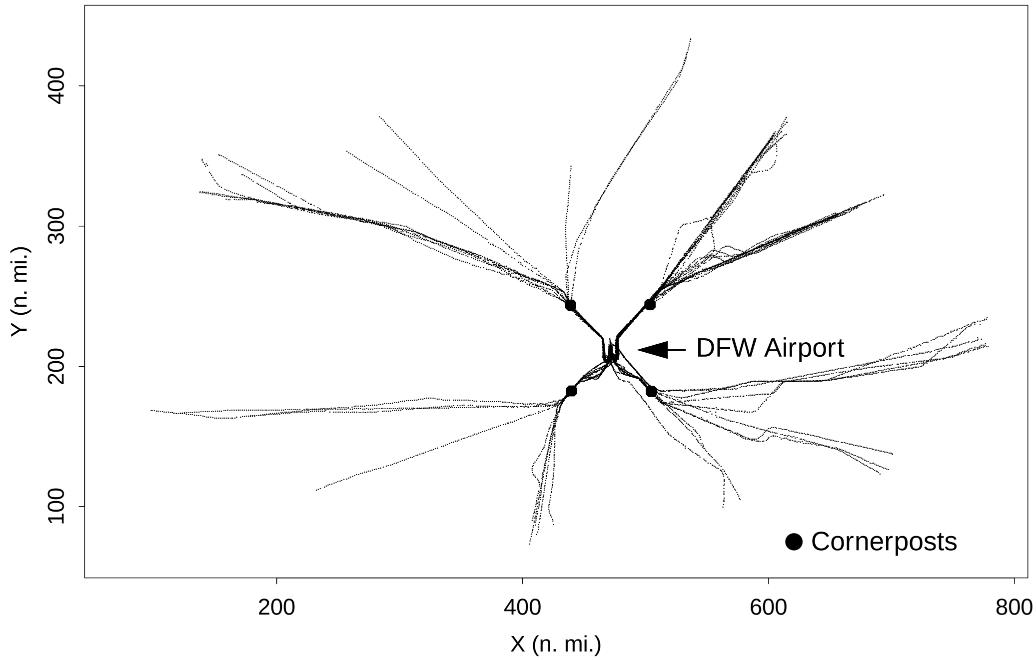

Figure 2(a). Aircraft tracks in Ft. Worth ARTCC and DFW TRACON during a typical rush period from 4:30 to 6:30 PM on April 22, 1998.

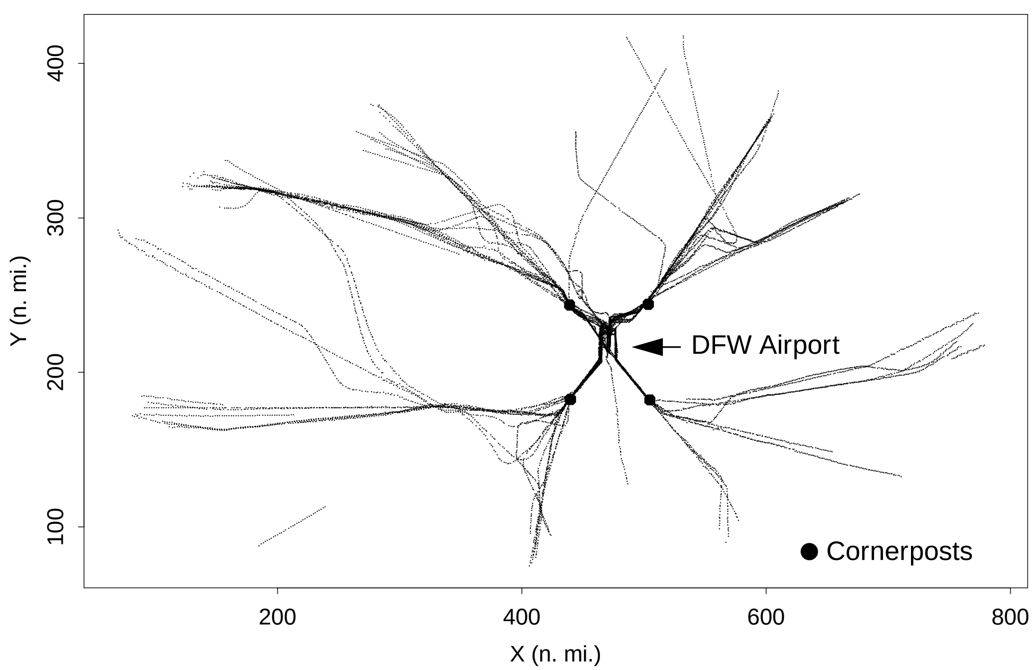

Figure 2(b). Aircraft tracks in Ft. Worth ARTCC and DFW TRACON during a heavy-traffic rush period from 10:00 AM to noon on April 14, 1998.

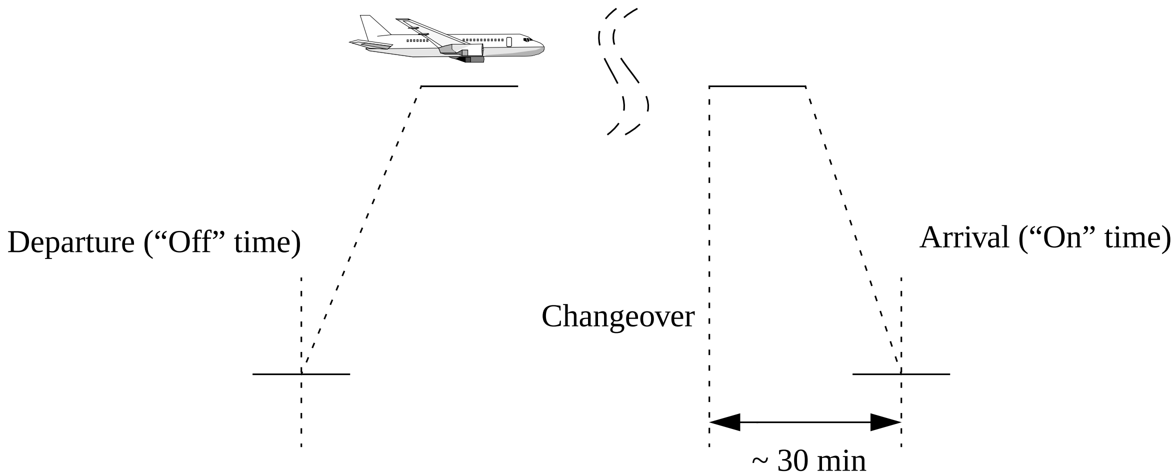

Figure 3. Time markers used by American Airlines.

minal area deviations differ with each day and arrival rush and are difficult for airlines to predict.

2.3 CTAS Time of Arrival Predictions

The Center TRACON Automation System (CTAS) was developed by the FAA and NASA to facilitate the work of air traffic service providers. CTAS is a suite of decision support tools that provides computer-generated advisories to assist both en route and terminal area controllers in efficiently managing arrival traffic. CTAS "build 2" consists of two sets of tools, the Traffic Management Advisor (TMA) and the passive Final Approach Spacing Tool (pFAST) (ref. 4). TMA generates runway assignments, landing sequences and landing times for arriving aircraft. A principal product of TMA is a sequence list, with any necessary per-aircraft metering delay for arriving aircraft entering TRACON airspace. Passive FAST provides updated runway and sequence advisories for arrival traffic within the TRACON. TMA and pFAST may be operated in concert or independently; when operated together their demonstrated benefits are additive.

The CTAS scheduling advisories are constructed from detailed aircraft trajectories, with input from flight plans, aircraft performance models, and real-time radar and weather data. Using these trajectories and controller-input airspace capacity and operational constraints, arrival times are predicted at several reference points, including the metering fixes and runway thresholds. The present analysis uses only the projected times for reaching the runway threshold, as given by the CTAS/TMA tool. The threshold crossing time, just seconds from touchdown, is a close approximation to the "wheels down" landing time recorded by the airline. This time marker is hereafter referred to simply as the "arrival time." For each incoming flight, CTAS provides two continually-updated projected arrival times. The "estimated time of arrival" (ETA) is calculated under the assumption that no further delay will be imposed before landing. The "scheduled time of arrival" (STA) is the ETA plus any delay that CTAS recommends to satisfy constraints of safety and capacity. CTAS maintains an optimal schedule of arrivals, subject to considerations of first-come first-serve order, minimum safe separation, and airport and runway throughput capacities.

The CTAS/TMA ETAs and STAs are calculated every 12 sec and recorded every 60 sec for subsequent data analysis. ETA values are updated continually from current radar and weather data until an aircraft has landed. STAs are updated until an aircraft is about 19 min from its metering fix (generally, about 30 min from landing), at which time they are "frozen" to provide stable values for controller use. The CTAS sequence lists and recommended per aircraft delay are provided to the ARTCC Traffic Management Coordinator (TMC) through a video display and to the sector controllers through their radar displays. The TMC's display includes timelines for traffic scheduled to the metering fixes and runways. A portion of a typical display pattern is illustrated in figure 4, where time is shown in the center column, with current time at the bottom. Aircraft are represented in the left-hand column by tags ordered according to the indicated ETAs.The right-hand column indicates the aircraft STAs, together with the delay needed to meet the STA. The times and aircraft tags move toward the bottom of the display as time advances.

Under CAP, the CTAS schedule timelines are displayed in the AAL SOC at a terminal adjacent to one of the airline's strategic flight operations positions. The aircraft tags of all non-AAL aircraft are de-identified to prevent a situation of perceived competitive advantage. This CAP display is the means by which CTAS scheduling information is shared with the airline (ref. 1).

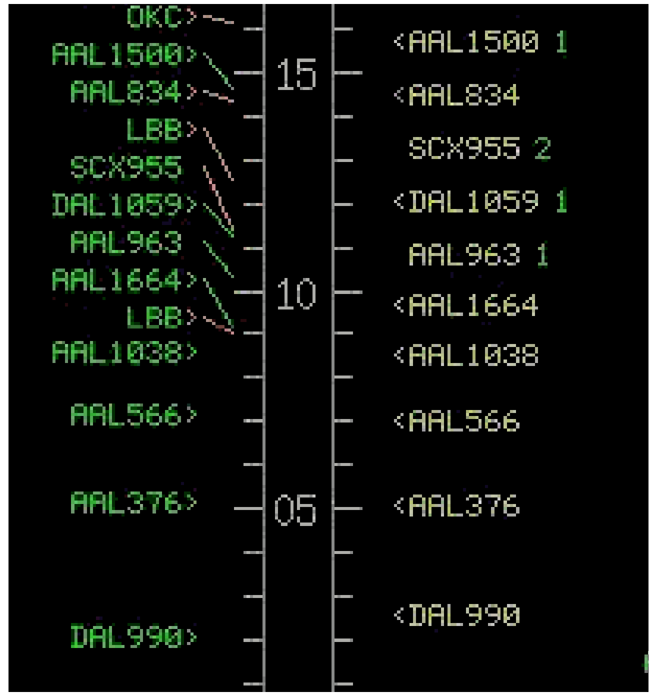

Figure 4. CTAS timeline display.

3. Analysis Methods

3.1 Raw Data

Basic diagnostic quantities for analyzing arrival time predictions were extracted from data recorded by the CTAS/TMA tool and from data recorded by American Airlines. These data were collected in April 1998, when the CAP Display System began continuous operational use at the AAL SOC. The raw data include actual arrival times of AAL flights at the DFW airport and arrival time estimates made prior to landing by both the airline and by CTAS. The AAL database provided the actual ON time for each landing flight, together with the E/ON estimate at takeoff, the changeover time, and the E/ON estimate at changeover. The CTAS data provided time-dependent ETA and STA values, recorded every 60 sec.

Figure 5 illustrates the rate of traffic flow into DFW during one of the days, April 14, on which data were collected. The horizontal axis is the time of day, and the vertical axis shows the number of aircraft landing within 10 min intervals. It is evident that there are distinct periods of heavy traffic—the "rush" periods. Markings at the bottom of the plot indicate four rushes selected for analysis, starting 10:00 AM, noon, 4:30 PM and 7:30 PM. Arrival time data for these rushes were extracted from CTAS and AAL recordings made on nine different days (April 13-17 and April 21-24), giving a total of 36 separate analysis periods. The traffic conditions during these times varied from relatively light, unmetered flow to heavy flow with metering at all approach fixes. The air traffic flow configuration at DFW during the analysis periods is described in table 1. Listed are the flow direction (north/south) and the airport acceptance rate (AAR), which is the number of aircraft that the TRACON can accept from the ARTCC per hour. During rushes with low AAR and high traffic volume, flights were subject to increased spacing and delay.

3.2 Derived Data

In the present analysis, the accuracy of a flight's predicted arrival time is measured as the difference between the actual and predicted landing times. With this prescription, the accuracy of each airline arrival time prediction is determined as the quantity "ON time minus E/ON time," using either the E/ON reported at takeoff or at changeover. The accuracy of each CTAS prediction is determined as the airline-supplied ON time minus either the CTAS ETA or the STA.

Because the arrival time predictions are time-dependent, recorded at takeoff and at changeover by the airline and every 60 sec by CTAS, conventions must be established for the times at which airline and CTAS predictions are compared. Accordingly, the

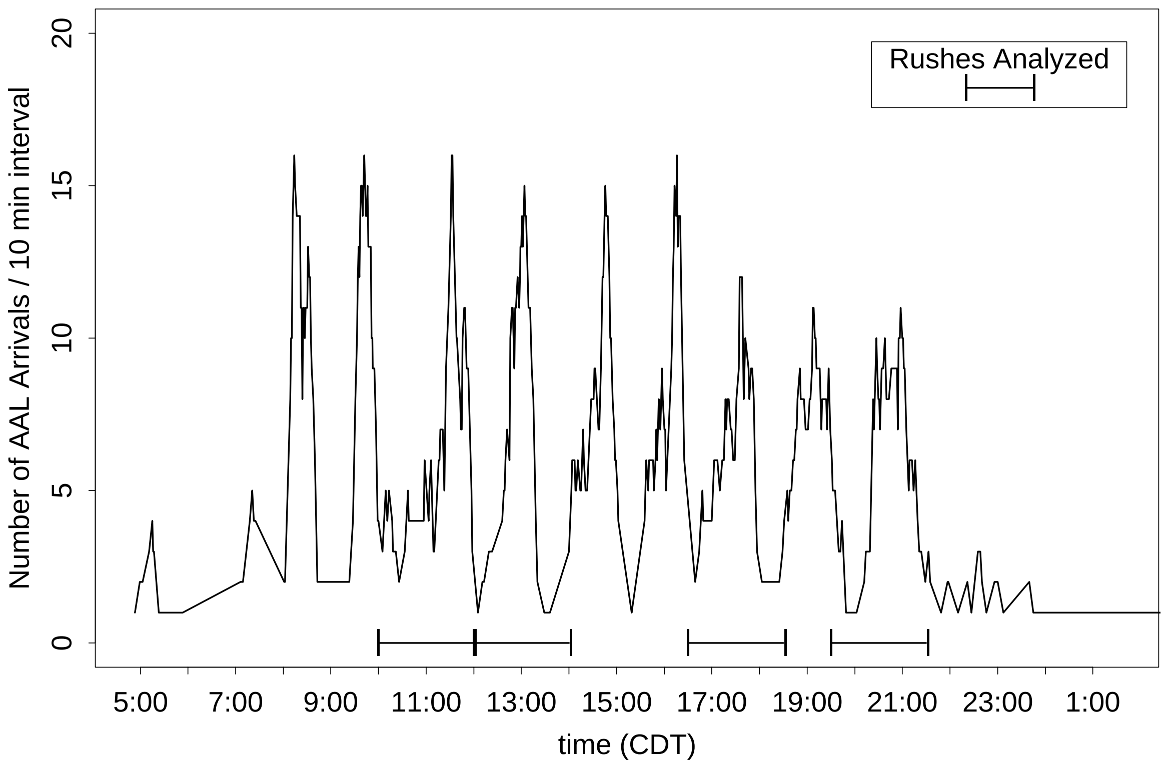

Figure 5. AAL traffic flow into DFW airport on April 14, 1998.

analysis uses the concept of a “horizon time” for each aircraft, defined as the continuously varying interval between the local time and the final landing time. An aircraft’s horizon time approaches zero as it reaches the runway. Arrival time accuracy was calculated at three standard horizon times: 15, 30 and 60 min before landing. The accuracy measure for the airline’s arrival time predictions (ON-E/ON) is based on the last E/ON reported before the horizon time, i.e., the E/ON at takeoff if the horizon time is before changeover, or the E/ON at changeover if the horizon time is at or after changeover. Similarly, the accuracy of the CTAS predictions (ON-ETA and ON-STA) uses the ETA or STA at the recording time closest to the horizon time.

With the above conventions, an accuracy measure was assigned to each arrival time predicted by the airline and by CTAS during the selected rush periods. These data provide the basis for the analytical studies described in the following sections.

3.3 Visualization and Interpretation Tools

Graphical and statistical methods were used to uncover trends and draw conclusions from the large quantity of diagnostic data. The fundamental visualization tool employed was a histogram plot showing the distribution of arrival time prediction accuracy during one rush period. Representative examples of this distribution are displayed in figure 6.

The data plotted in figure 6 refer to AAL flights arriving at DFW during a 2 hour rush period starting 4:30 PM on April 22, 1998. A track diagram depicting the trajectories of these flights in Center and TRACON airspace is given in figure 2(a). In figure 6, the top histogram was derived from AAL-recorded data and the bottom histogram from CTAS data. On each of these plots, the horizontal axis represents the accuracy of predicted arrival times (actual minus predicted time), and the vertical axis shows the number of aircraft with prediction accuracy within 1 min intervals. The measure of accuracy was taken as ON-E/ON for the airline predictions and ON-STA for the CTAS predictions. Positive values correspond to aircraft that arrived later than predicted and negative values to air-

Table 1. Air Traffic Configuration at DFW Airport

Period		AAR, Flow Direction
13 April 99	1000 - 1200 CDT	120, South
	1200 - 1400	120, South
	1630 - 1830	108, South
	1930 - 2130	120, South
14 April	1000 - 1200	114, South
	1200 - 1400	114, South
	1630 - 1830	120, South
	1930 - 2130	120, South
15 April	1000 - 1200	114, South
	1200 - 1400	114, South
	1630 - 1830	120, South
	1930 - 2130	120, South
16 April	1000 - 1200	120, North
	1200 - 1400	120, North
	1630 - 1830	120, North
	1930 - 2130	120, North
17 April	1000 - 1200	126, North
	1200 - 1400	126, North
	1630 - 1830	126, North
	1930 - 2130	126, North
21 April	1000 - 1200	126, North
	1200 - 1400	126, North
	1630 - 1830	126, North
	1930 - 2130	126, North
22 April	1000 - 1200	126, North
	1200 - 1400	126, North
	1630 - 1830	126, North
	1930 - 2130	126, North
23 April	1000 - 1200	120, South
	1200 - 1400	120, South
	1630 - 1830	120, South
	1930 - 2130	120, South
24 April	1000 - 1200	120, South
	1200 - 1400	120, South
	1630 - 1830	120, South
	1930 - 2130	120, South

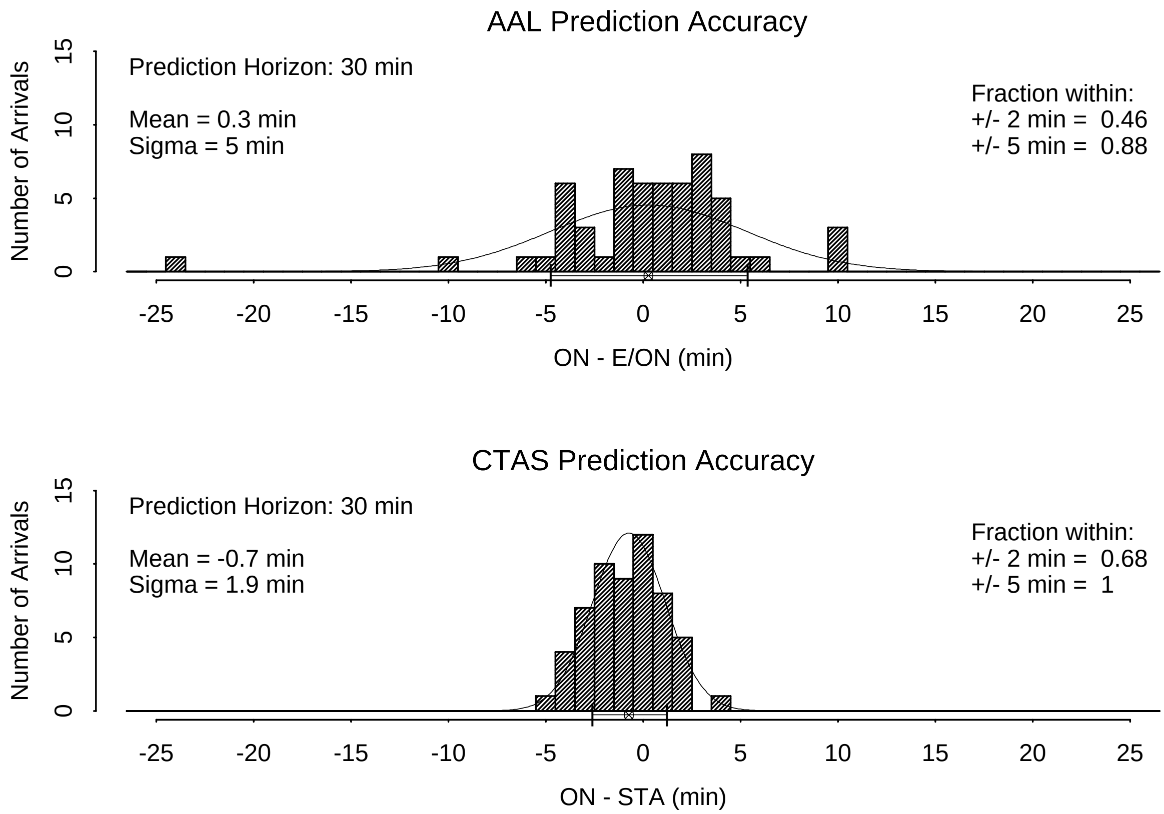

Figure 6. AAL and CTAS time of arrival prediction accuracy at the 30 minute prediction horizon during the 4:30-6:30 PM rush on April 22, 1998.

craft that arrived early. For instance, the top plot indicates that three aircraft arrived 10 min later than the airline predictions. Because the horizon time for this example, 30 min from landing, is also the average time at which changeover E/ON estimates were reported, about half of the airline's arrival time predictions were based on the changeover E/ON and about half on the E/ON at takeoff. As an aid in visualizing the shapes of the data distributions, each histogram is overdrawn with a Gaussian curve fit to the mean and standard deviation of the prediction accuracy values.

To further assist in interpreting and comparing data sets, the numerical values of several statistically-based properties are shown on each histogram plot. These include the mean value of the arrival time prediction accuracy and three quantities representing the width of the accuracy distribution: the standard deviation with respect to the mean, and the fractions of flights arriving within ± 2 min and within ± 5 min of their predicted times.

In the final stage of the analysis, airline and CTAS predictions for all 36 rush periods were summarized and compared. Section 4.3 describes this procedure in detail.

4. Analysis Results

4.1 Typical Rush Period

The data in figure 6 illustrate a rush period with moderate traffic and minimal delay. Each histogram is an accuracy distribution for a set of 57 AAL flights which landed during the 2 hour period beginning 4:30 PM on April 22, 1998, and had CTAS-recorded STAs at the prediction horizon 30 min prior to landing. It is seen that the mean arrival time accuracy of these aircraft is 0.3 min late in the airline predictions and 0.7 min early in the CTAS predictions. A mean accuracy within 1 min is typical for the rushes studied, occurring in 75% of the CTAS predictions and 70% of predictions by the airline.

The observation that the mean per-aircraft arrival time error is generally small and comparable in the airline and CTAS predictions suggests that this statistic, by itself, is not a meaningful measure of arrival time prediction accuracy. The mean prediction accuracy may be especially misleading if large positive and negative values cancel in the averaging. That this indeed occurs for the rush shown in figure 6 is evidenced by the larger width of the distribution representing the airline predictions. A better indicator of the spread in the data from aircraft arriving significantly early or late could thus be a statistic measuring the mean absolute value of the prediction accuracy. One such statistic is the standard deviation with respect to the mean, shown on the plots with the entry labeled "sigma." Because sigma is derived from the mean square of the accuracy values, it is especially sensitive to the largest values present. By this measure, the CTAS arrival time predictions (sigma = 1.9 min) are seen to offer substantial improvement over predictions by the airline (sigma = 5.0 min).

An alternative measure of the spread in the prediction accuracy is provided by entries on each histogram plot giving the fraction of arrival times predicted to a specified accuracy, either within ± 2 min or within ± 5 min of the actual arrival time. For the typical rush of figure 6, it is seen that the airline predictions are accurate to within ± 2 min for 46% of the flights, but that CTAS achieves this accuracy for a significantly larger 68% of all flights. Moreover, accuracy within ± 5 min was achieved in 88% of the airline predictions, but in all 100% of the predictions by CTAS.

Figure 6 also shows that the CTAS data contain fewer outlier points representing prediction anomalies large enough to disrupt flight operations. It has already been noted that three flights arrived 10 min later than the airline predictions, but it is even more significant that one flight arrived 24 min earlier. With such uncertainty in the arrival time, the airline was likely unprepared with a gate for the flight. In contrast, no flight arrived more than 5 min earlier or 4 min later than the times predicted by CTAS.

Additional analyses have shown that the improvement in arrival time accuracy offered by CTAS at the 30 min horizon of the "typical" rush period of figure 6 extends to other rushes and prediction times. The histogram plots in figure 7 compare airline and CTAS arrival time predictions for the typical rush at horizon times 15, 30 and 60 min before landing. The diagrams in the center for the 30 min horizon duplicate figure 6. The 60 min horizon is generally close to the time when an aircraft is acquired by center radar and first appears in the CTAS recording. Consequently, some aircraft are not yet recorded by CTAS at this horizon time, and fewer data points are plotted. The 30 min horizon is close to the time when the CTAS STA is frozen, and the 15 min horizon is approximately the time when aircraft enter the TRACON airspace, where controllers rely on pFAST rather than TMA delay advisories. It is evident that the airline's arrival time predictions are similar at the 60 and 30 min horizons, as measured by the accuracy distribution widths and the number of outlier points. These predictions improve slightly by the 15 min horizon time, when most changeover estimates have been received. The improvement is evidenced by a 40% reduction in the standard deviation parameter. In contrast, CTAS predictions improve between the 60 and 30 min horizons but remain nearly constant inside of the 30 min horizon, where STA values are frozen. More significantly, however, it is seen that the CTAS predictions are more accurate at all horizon times. The widths of CTAS accuracy distributions are 50-70% of corresponding airline distribution widths, and, whereas the airline distributions contain outlier points with 10-24 min errors at each horizon time, there is only one CTAS outlier. This occurred at the 60 min horizon, when an arrival time forecast from an initial flight-plan-based STA was inaccurate by 19 min. Upon receipt of radar positional data, CTAS improved the aircraft's STA, and, by the 30 min horizon, it no longer appeared as an outlying point.

A similar set of accuracy distribution histograms in figure 8 demonstrates that CTAS arrival time accuracy at small prediction horizons may be improved by using ETAs in place of STAs. These plots refer to the same rush period and prediction horizons used for figure 7. The top row of plots showing airline prediction accuracy is identical in the two figures, but the bottom row is changed in figure 8 to show CTAS accuracy measured as ON-ETA. It should be recalled that ETAs are calculated under the assumption that aircraft will have no further delay, and that the updating of ETAs continues beyond the time at which STAs are frozen. Thus, while the CTAS STAs are generally preferred in

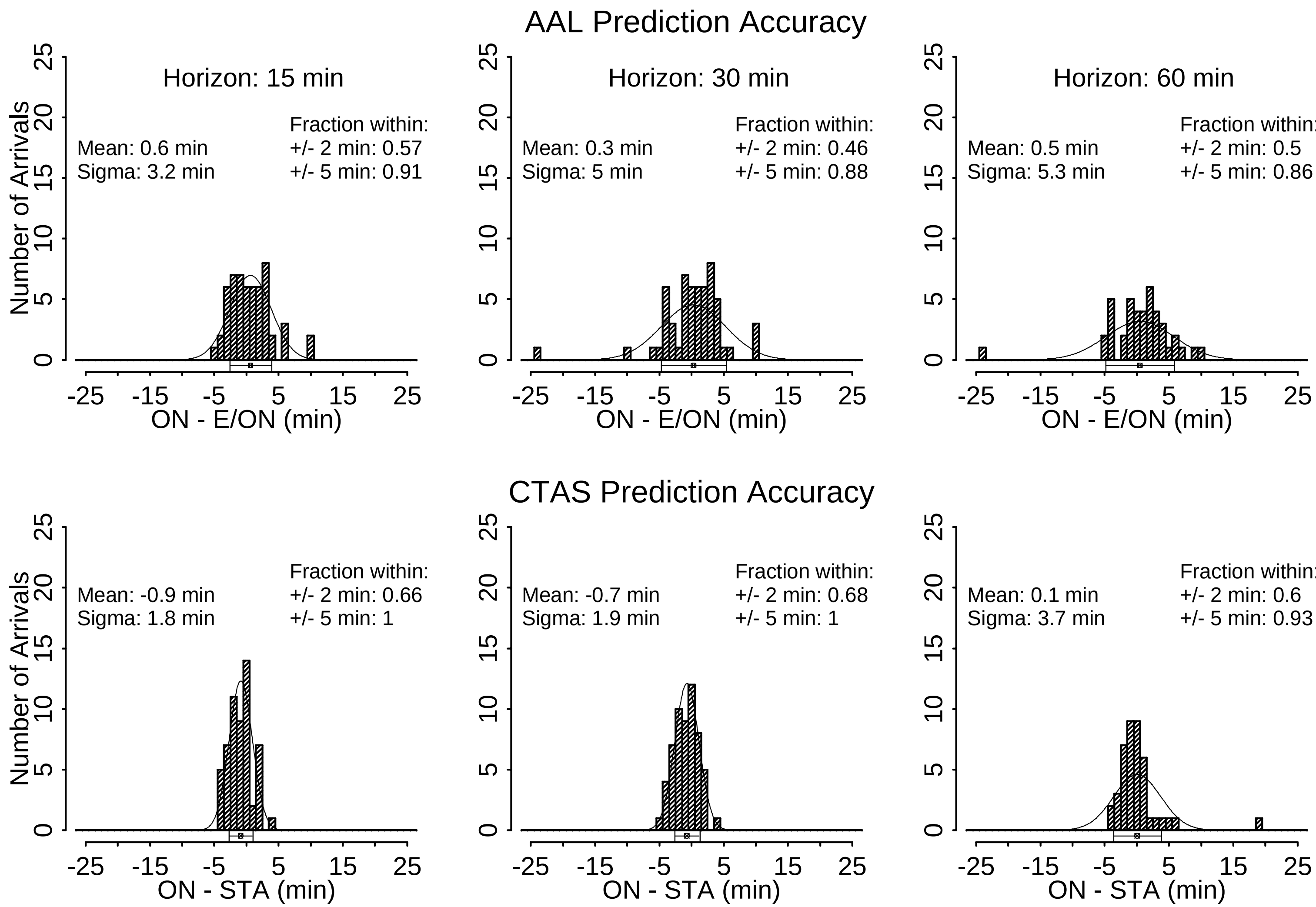

Figure 7. CTAS STA-based versus AAL time of arrival prediction accuracy during the 4:30-6:30 PM rush on April 22, 1998.

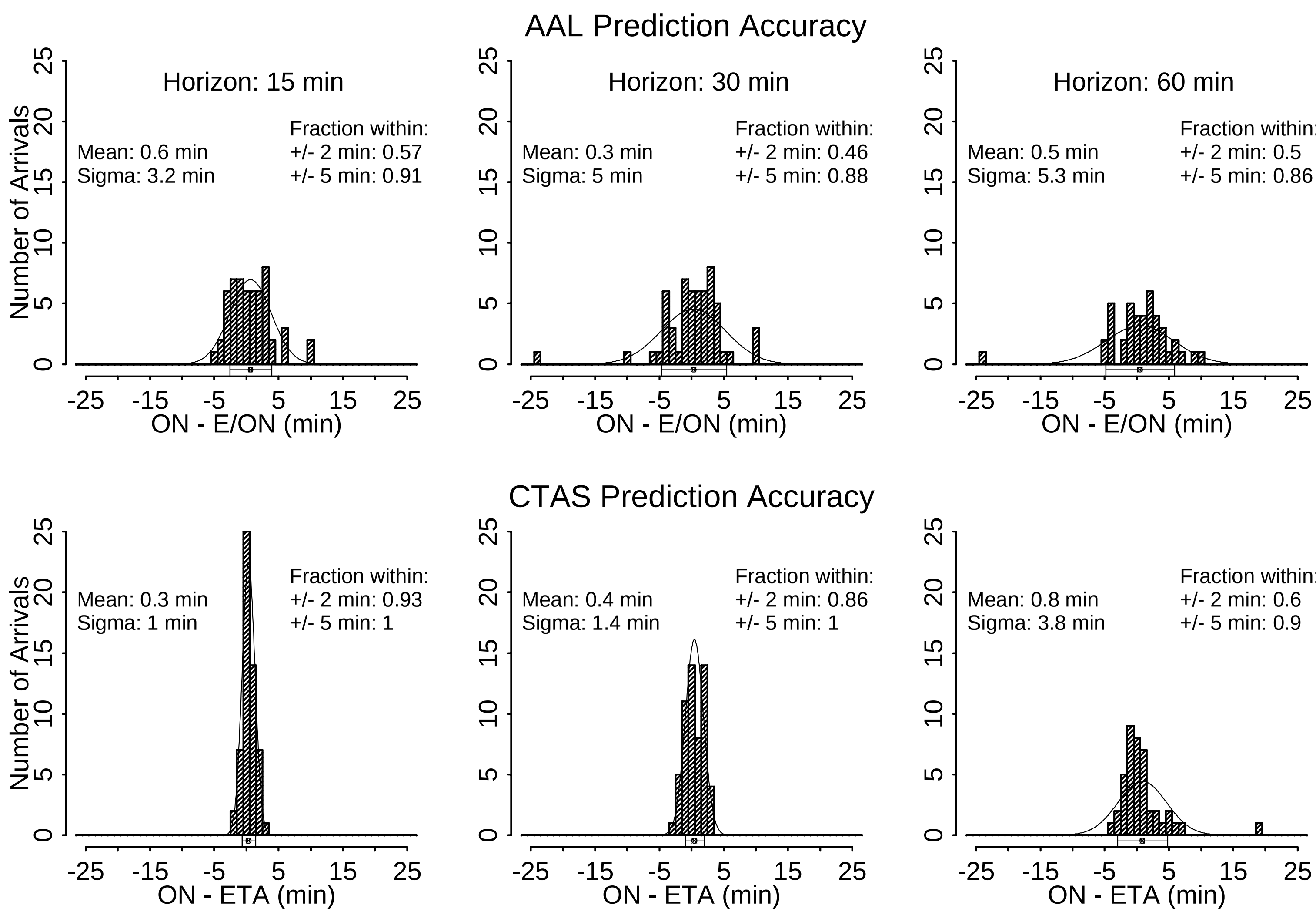

Figure 8. CTAS ETA-based versus AAL time of arrival prediction accuracy during the 4:30-6:30 PM rush on April 22, 1998.

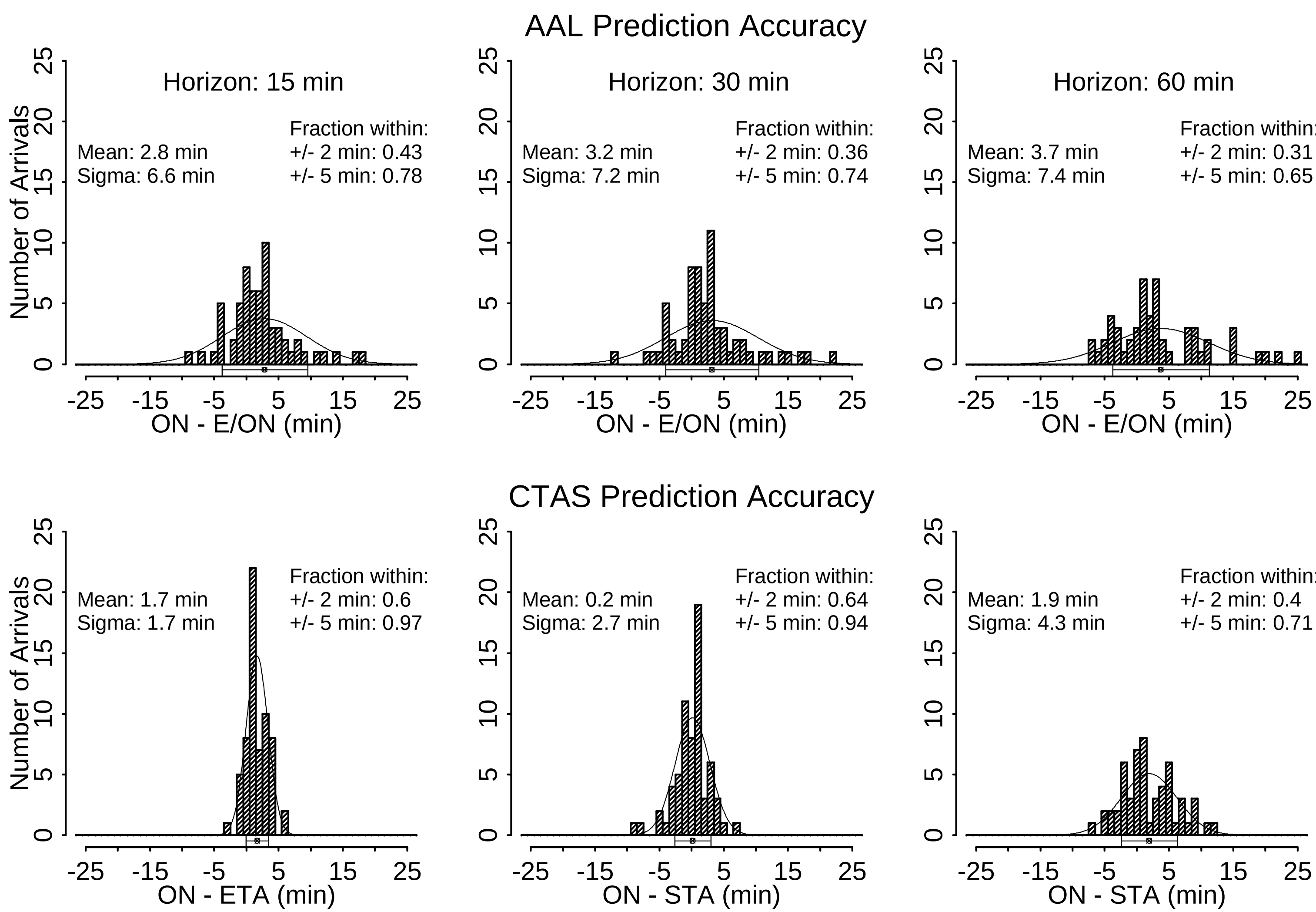

Figure. 9. CTAS ETA/STA-based versus AAL time of arrival prediction accuracy during the 10:00-noon rush on April 14, 1998.

forecasting arrival times (especially during rushes with significant delay), the ETA may become the better predictor inside the “freeze horizon” at about 30 min before landing. Moreover, the ETA continues to improve and may become a highly accurate predictor as aircraft approach landing and all necessary delay has been absorbed. These trends are evident in figure 7 as a steepening and narrowing of the ETA accuracy distribution with decreasing prediction horizon. It is seen that 93% of ETAs are accurate to within 2 min at the 15 min horizon, whereas, from figure 6, only 66% of the STAs have this precision. In this example, the ETAs also show a distinct, although less dramatic, advantage at the 30 min horizon, but this advantage may not hold during periods of larger delay. Therefore, further accuracy comparisons in this report are based on ETAs at the 15 min prediction horizon and on STAs at all larger horizon times.

4.2 Large-delay Rush Period

Figure 9 illustrates arrival time accuracy for a rush with particularly heavy traffic and large delay, covering the period from 10:00 to noon CDT on April 14, 1998. This is the period for which aircraft tracks were shown in figure 2(b). The top row of histogram plots again shows the accuracy of the airline’s arrival time predictions and the bottom row the accuracy of CTAS predictions. The format deviates slightly from previous figures in that, for the reasons given in section 4.1, CTAS predictions are based on the aircraft STAs at the 60 and 30 min horizons and on ETAs at the 15 min horizon.

The airline has more difficulty than CTAS in forecasting this high-traffic rush, as evidenced by the larger widths of its accuracy distributions and by the larger number flights arriving considerably early or late. If flights with arrival times deviating by 10 or more minutes from the airlines latest prediction are designated as “outliers,” then the airline accuracy distribution is seen to have 10 outliers at the 60 min horizon, 8 at 30 min, and 5 at 15 min. Most of these flights arrive late—one as much as 25 min late. The CTAS predictions, on the other hand, show in total only 2 outliers, both at the 60 min horizon. At the 15 min horizon, CTAS predicts all arrivals to within 6 min.

Arrival time uncertainty can seriously disrupt an airline’s strategic planning and operations efficiency. For example, in the instance of the aircraft arriving an unexpected 25 min late, the airline likely held a connecting flight that it should have released. The incorrect decision to hold might then have initiated a chain of schedule disruptions propagating throughout the system.

4.3 Statistical Summary for All Rush Periods

The analysis results presented in previous sections refer to a single rush period, either the “typical” rush or the sample “high-delay” rush. In this section, results for all rushes studied are presented as a series of diagrams in summary format, beginning in figure 10 with diagrams summarizing the uncertainty in arrival time predictive accuracy as measured by the widths of accuracy distributions. The data in this figure were derived from 72 histogram distributions representing airline and CTAS arrival time accuracy at the 30 min horizon during 36 rush periods (4 rushes per day on 9 days). The standard deviation of the accuracy distributions is plotted as a function of the time of day at mid-rush, i.e., CDT one hour after the start of the two-hour rush period. The 18 points at each rush time refer to CTAS and airline predictions on each of the 9 days, with the airline data represented by triangles and the CTAS data by squares. Open symbols refer to the individual rush periods and closed symbols to averages over the 9 days.

At each rush time shown in figure 10, the standard deviation points for airline accuracy distributions lie generally above the corresponding CTAS points, with an average factor of 2 separation. This distinction between airline and CTAS predictions is especially evident for the two rush periods on April 14 indicated with arrows. The period centered at 11:00 CDT is the high-traffic, large-delay rush for which difficulties in the airline’s arrival time forecast were discussed in section 4.2. Difficulties with the second period at 20:30 CDT on April 14 cannot be easily explained by the traffic volume or delay, both of which are average for the rushes at this time. During these two periods, the standard deviations for the airline accuracy distributions are abnormally large (7.2 and 7.3 min), whereas much smaller widths for the corresponding CTAS distributions (2.7 and 1.9 min) indicate that CTAS experienced no exceptional predictive difficulty. Finally, it should be noted, from the small variation in the solid-point averages, that the improvement

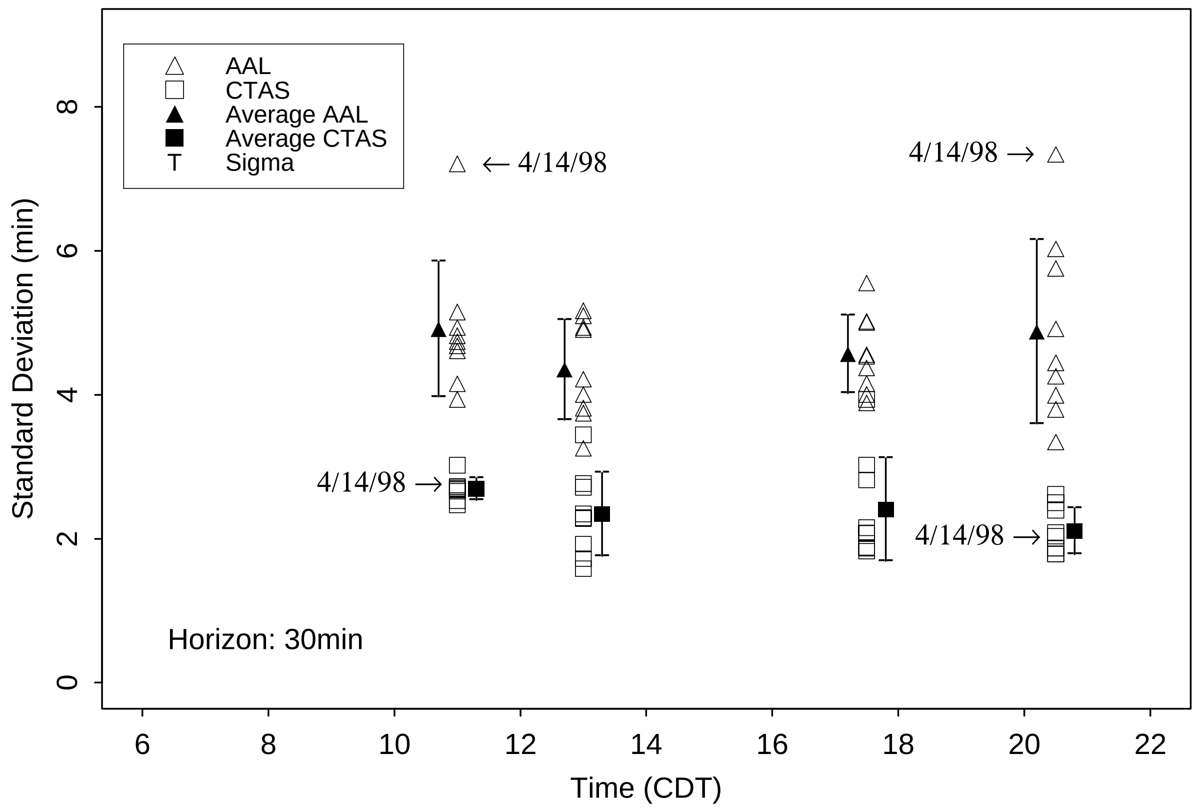

Figure 10. Standard deviation of AAL and CTAS arrival time accuracy distributions for all rush periods.

in predictive accuracy offered by CTAS is consistent over rush times throughout the day.

The conclusion that the CTAS advantage seen in figure 10 extends to other prediction horizons and accuracy measures is anticipated from the analysis of selected rushes in sections 4.1 and 4.2 and confirmed by the additional summary diagrams in figures 11, 12 and 13. These figures summarize 5 diagnostic measures of prediction accuracy, calculated at 3 horizons during the 36 rush periods. The plot format follows figure 9, but only the 9 day average at each rush time is shown, and, following the convention established in section 4.1, arrival time accuracy is calculated as ON-E/ON for airline predictions, ON-ETA for CTAS predictions at the 15 min horizon and ON-STA for CTAS predictions at the 30 and 60 min horizons. A supplementary numerical table (table 2) lists averages over the set of 4 rush times, together with standard deviations relative to that average.

The first row of plots in figure 11 summarizes values for the arithmetic means of airline and CTAS prediction accuracy distributions at horizons 15, 30 and 60 min from landing. An obvious feature of this figure is the similarity of the airline and CTAS data points: mean accuracy values are nearly identical at most rush times and show similar timewise variation. At the 60 min horizon, predominantly positive accuracy values indicate that many flights arrive later than predicted. This result is expected because delay is often imposed closer to landing and not anticipated 60 min ahead. At the 30 min horizon, the prediction accuracy has predominantly negative sign, reflecting the tendency for controllers to “frontload” the TRACON at the start of the rush, sending in some aircraft ahead of schedule to fill up available slots in the landing sequence. By the 15 min horizon, most assigned delay has been absorbed, and predictions are generally accurate to within 30 sec. Averaged over all aircraft, these trends have such comparable effect on the airline and CTAS

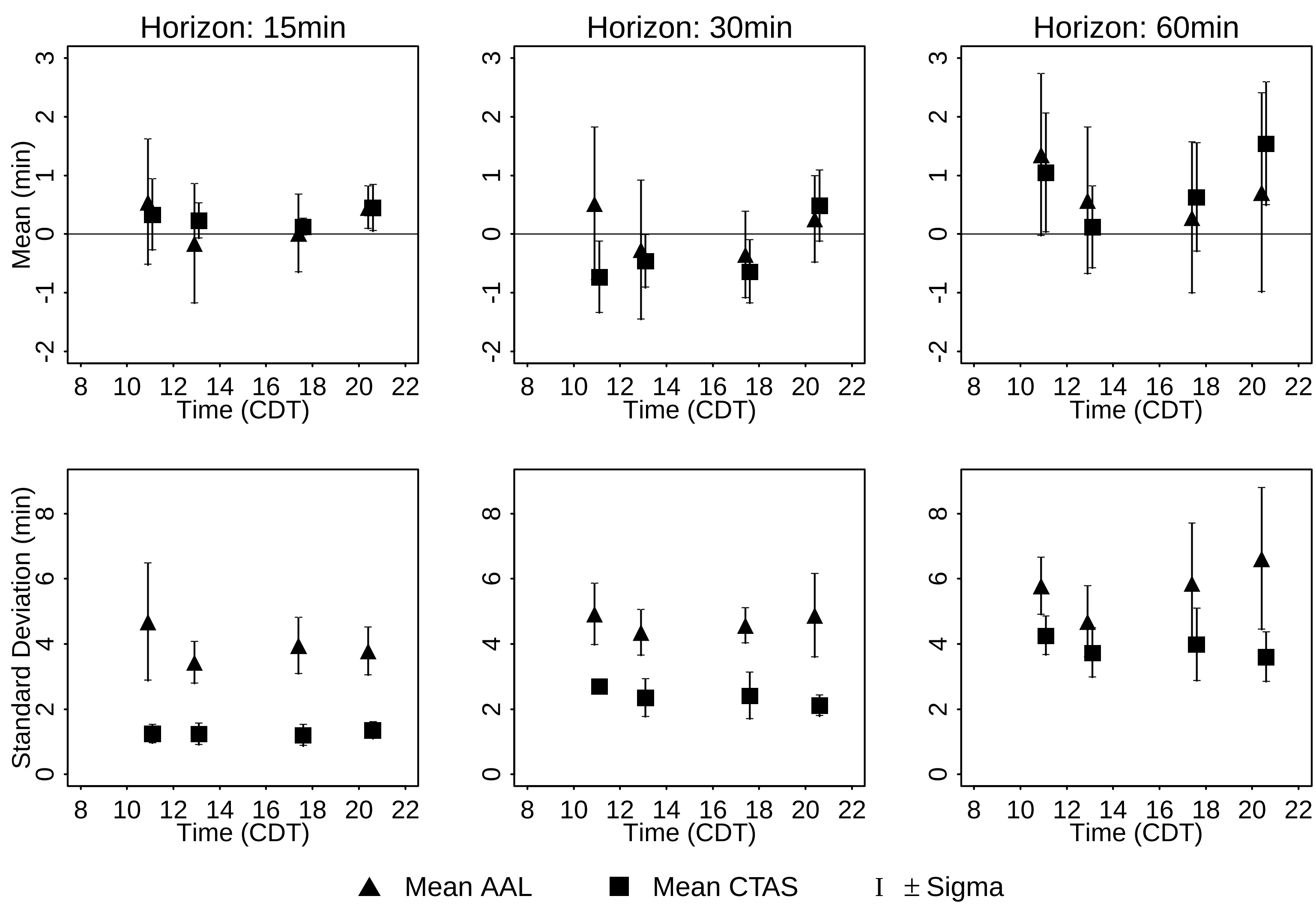

Figure 11. Mean and standard deviation of AAL and CTAS arrival time accuracy distributions, averaged over 9 test days.

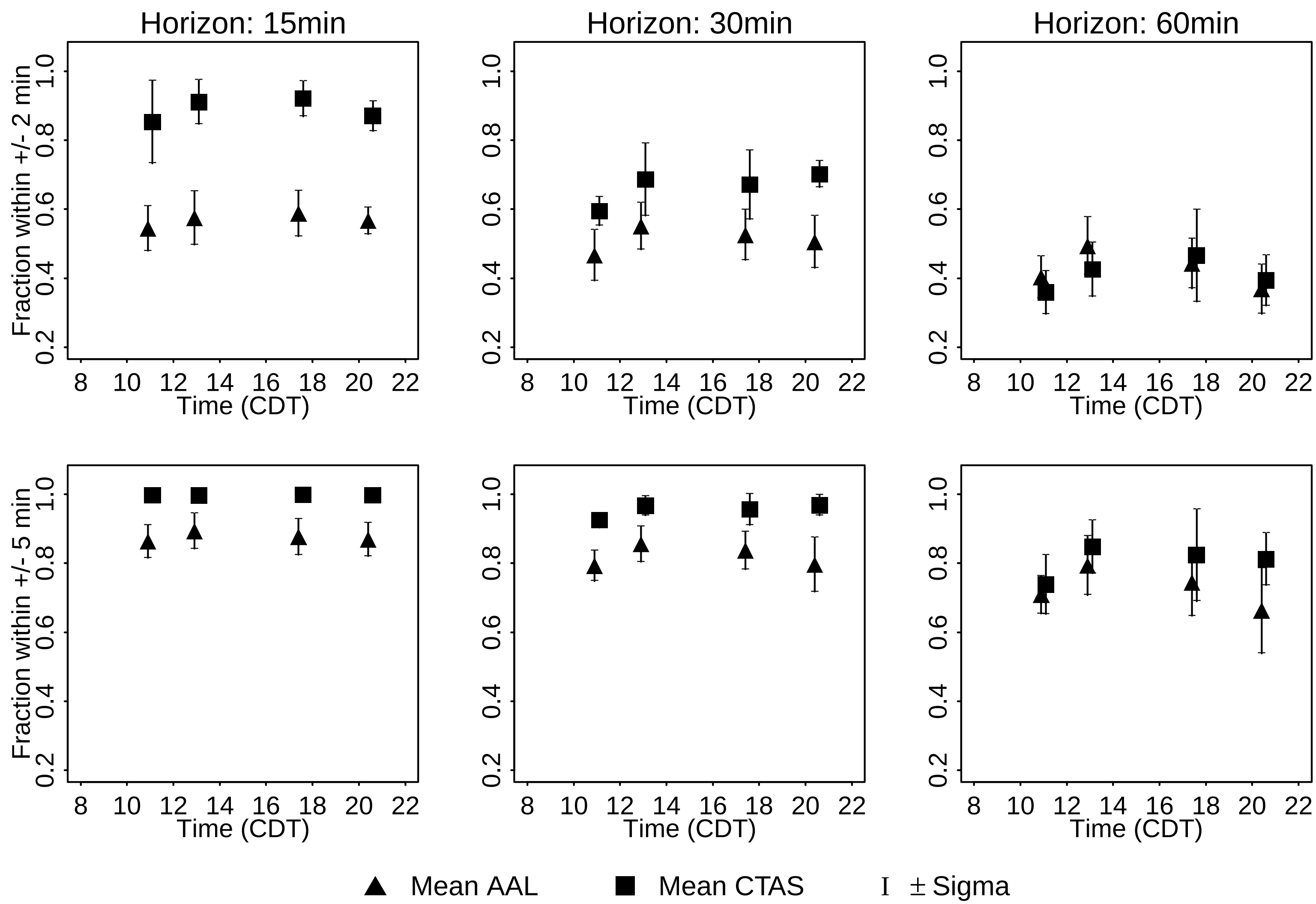

Figure 12. Fraction of AAL and CTAS arrival time predictions accurate to within 2 and 5 min, averaged over 9 test days.

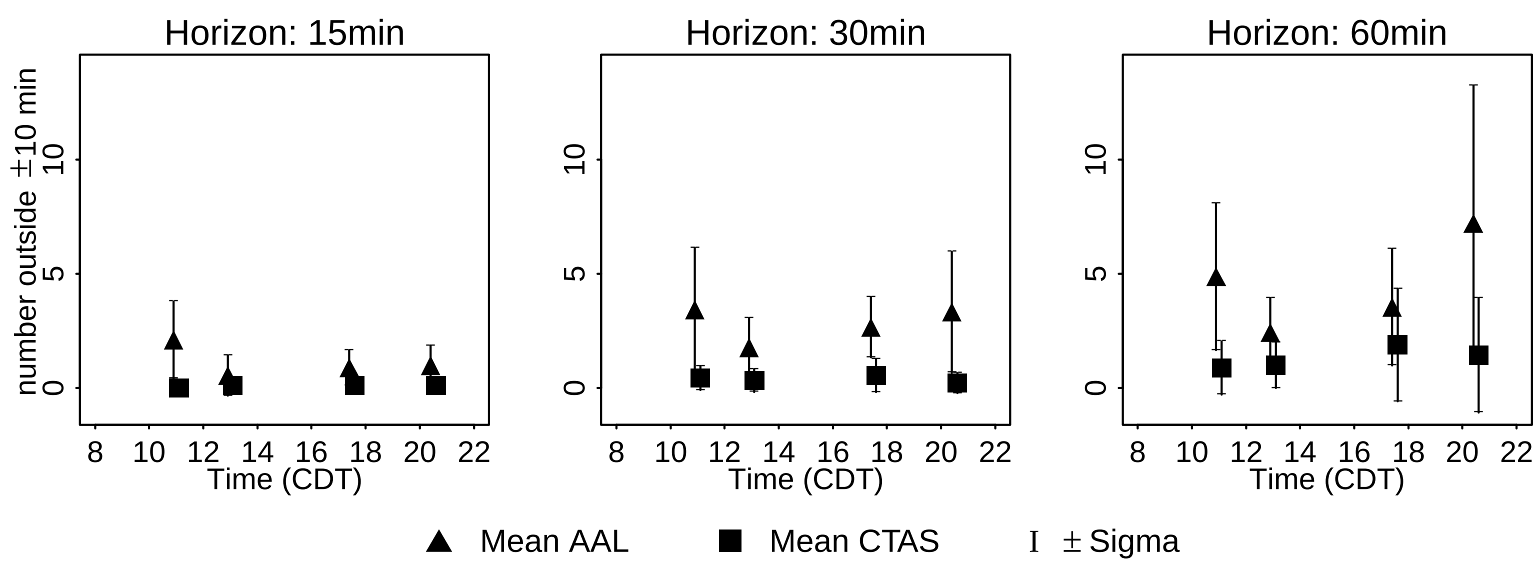

Figure 13. Fraction of AAL and CTAS arrival time predictions inaccurate by more than 10 min, averaged over 9 test days.

Table 2. Time-averaged Measures of Prediction Accuracy

Mean

	Prediction Horizon		
	15 min	30 min	60 min
AAL	0.21 ± 0.85	0.04 ± 1.04	0.73 ± 1.41
CTAS	0.28 ± 0.40	-0.34 ± 0.72	0.83 ± 1.04

Standard Deviation

	Prediction Horizon		
	15 min	30 min	60 min
AAL	3.96 ± 1.16	4.67 ± 090	5.73 ± 1.67
CTAS	1.25 ± 0.29	2.39 ± 0.52	3.89 ± 0.83

Fraction within ± 2 min

	Prediction Horizon		
	15 min	30 min	60 min
AAL	0.57 ± 0.06	0.51 ± 0.08	0.43 ± 0.08
CTAS	0.89 ± 0.08	0.66 ± 0.09	0.41 ± 0.10

Fraction within ± 5 min

	Prediction Horizon		
	15 min	30 min	60 min
AAL	0.88 ± 0.05	0.82 ± 0.06	0.73 ± 0.10
CTAS	1.00 ± 0.01	0.95 ± 0.04	0.81 ± 0.10

Number of outliers ≥ 10 min

	Prediction Horizon		
	15 min	30 min	60 min
AAL	1.1 ± 1.2	2.8 ± 2.1	4.5 ± 4.0
CTAS	0.1 ± 0.3	0.4 ± 0.5	1.3 ± 1.9

arrival time predictions, that an analysis based on the arithmetic mean accuracy measure reveals no particular advantage for either set of values.

A more definitive parameter for comparing airline and CTAS arrival time statistics is provided by the standard deviation of the prediction accuracy distributions. Plots summarizing this measure for all rushes and prediction horizons are displayed in the second row of figure 11, with the plot at the 30 min horizon duplicating data shown in figure 10. As noted in the discussion of figure 10, the standard deviation measures the spread in accuracy values with an algorithm especially sensitive to the effect of "outlier" points. In figure 11, the CTAS data points lie consistently below the corresponding airline points, indicating superior CTAS predictive accuracy at all rush and horizon times. Moreover, the improvement with CTAS is seen to be greatest for predictions made close to the time of landing. This qualitatively evident trend may be quantified with the data in table 2, from which a simple calculation shows that the ratio of CTAS to airline standard deviation values decreases from 0.7 to 0.3 as the horizon decreases from 60 to 15 min.

The greater precision of the CTAS arrival time predictions is again evident from the plots in figure 12, which show the fraction of predictions accurate to within 2 and 5 min. As in previous diagrams, the improvement with CTAS is most obvious at the smaller horizon times. At the 60 min horizon, the CTAS advantage is minimal and seen only in the slightly larger fraction of predictions accurate to within 5 min. Table 2 shows this fraction to be 81% for CTAS versus 73% for the airline, averaged over all rush periods. At the 30 min horizon, CTAS predictions had an average accuracy of 66% within 2 min and 95% within 5 min, versus the accuracy of 51% and 82% achieved by the airline. By the 15 min horizon, CTAS predicted 89% of all flights within 2 min and a full 100% within 5 min, a dramatic improvement over the fractions 57% and 88% achieved by the airline.

A final set of summary plots in figure 13 illustrates the potentially most valuable advantage for CTAS predictions: a significant reduction in the number of "outlier" flights with arrival time errors greater than or equal to 10 min. These plots reveal a distinct improvement with CTAS at all rush and horizon times, but in this case the greatest benefit occurs at the 60 min horizon. At that time, the airline predictions had almost 5 outliers per rush period, whereas with CTAS the number of large magnitude errors was reduced to approximately one.

The above analyses using a variety of accuracy measures to contrast CTAS and airline arrival time predictions compellingly demonstrate the benefits derived from CTAS scheduling information, especially during heavy rush periods and for those flights most difficult to forecast by the airline's traditional methods. This improved predictive ability should have considerable value in minimizing the disruptive effects of miscalculated delay on airline operations.

5. Concluding Remarks

An analysis of data recorded during an experimental test of the airline-CTAS information exchange system has demonstrated the utility of CTAS air traffic management advisory software in predicting accurate aircraft arrival times. Compared with traditional airline arrival prediction, CTAS more precisely forecasts ATC-imposed delay. Especially significant is the reduction in prediction errors of 10 or more minutes, which could invoke large disruptions in airline hub and spoke operations. Furthermore, whereas conventional airline schedules are not updated beyond about 30 minutes from landing, CTAS's predicted landing times become increasingly accurate as aircraft near the terminal. Finally, the benefits realized from CTAS are greatest during periods of heavy traffic and large delay, the very conditions that cause the most disruption to an airline's operational efficiency.

Although the present research did not include a comprehensive analysis of operational benefits accrued by the airline, an assessment of benefits to American Airlines during the April 1998 CAP Display System testing has been given by Zelenka et al. (ref. 1). These authors report that, on several occasions during the test period, AAL was assisted in equipment move-ups and flight shuffling and in preventing diversions for flights into its DFW hub. Moreover, the improvements in arrival time prediction and strategic fleet arrival planning were accomplished with no adverse impact on FAA air traffic control operations.

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13. ABSTRACT ***(Maximum 200 words)***

Benefits from information sharing between an air traffic service provider and a major air carrier are evaluated. Aircraft arrival time schedules generated by the NASA/FAA Center/TRACON Automation System (CTAS) were provided to the American Airlines System Operations Control Center in Forth Worth, Texas, during a field trial of a specialized CTAS display. A statistical analysis indicates that the CTAS schedules, based on aircraft trajectories predicted from real-time radar and weather data, are substantially more accurate than the traditional airline arrival time estimates, constructed from flight plans and en route crew updates. The improvement offered by CTAS is especially advantageous during periods of heavy traffic and substantial terminal area delay, allowing the airline to avoid large predictive errors with serious impact on the efficiency and profitability of flight operations.

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